Estimating Small Grain Equivalents of Shrub-Dominated Rangelands for Wind Erosion Control

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ABSTRACT

A wind erosion equation, which estimates average annual erosion, requires that all vegetative cover be expressed as dry biomass per unit area of flat small grain equivalent $(SG)_e$. For a standing vegetative canopy, the $(SG)_e$ depends on the magnitude of the friction velocity reaching an underlying erodible surface. The soil surface friction velocity, and thus $(SG)_e$, was shown to be a function of aerodynamic roughness length of the canopy and the product of a drag coefficient and plant area index. Aerodynamic roughness, as well as canopy silhouette area and mass distribution, were measured in sand sagebrush (*Artemisia filifolia* Nutt.) and yucca (*Yucca elata* Englem.) canopies. Estimating equations were developed to predict $(SG)_e$ of the sagebrush and yucca canopies using either above-ground dry biomass or plant area index as inputs. Additional estimating equations were developed to predict plant area or plant mass from simple geometric measurements of yucca and sagebrush. Finally, for shrub or stubble canopies in which $(SG)_e$ prediction parameters have not been measured, a way to approximate the prediction parameters using an estimate of canopy aerodynamic roughness length was developed.

INTRODUCTION

Large areas in the U.S. are covered with shrub-dominated rangelands. Among the most important shrub-dominated rangeland ecosystems where wind erosion can be a problem are the following: sagebrush, pinyon-juniper, creosote-tarbush, mesquite, and shinnery oak.* Nutrients are often concentrated near the surface in rangeland soils, and soil trapped in wind erosion catchers on rangelands on the average has higher nutrient enrichment ratios than soil eroding from croplands (Hagen and Lyles, 1985).

Because rangeland productivity is already often limited by soil water-holding capacity and/or nutrient availability, it is important to consider wind erosion control in design and evaluation of rangeland management systems. Current procedures for evaluating wind erosion control practices utilize the wind erosion equation (Woodruff and Siddoway, 1965). To use the equation, one must express all vegetative cover in terms of its equivalent to a small grain dry above-ground biomass reference standard $(SG)_e$. Prediction equations have been developed to predict $(SG)_e$ for several range grasses (Lyles and Allison, 1980), as well as flat and standing crop residues (Lyles and Allison, 1981). However, $(SG)_e$ prediction equations are lacking for various shrub species to evaluate their ability to control wind erosion.

The standard procedure to evaluate $(SG)_e$ of plants is to conduct laboratory wind tunnel tests on the plants at various plant populations. Shrubs present special challenges, however, because many are too large to fit in the wind tunnel test facility, and the resources to test a large number of species are not available.

The first objective of this study was to begin developing $(SG)_e$ prediction equations for shrub canopies. Two species were selected for initial study because they are widespread and have contrasting plant structures. These species were sand sagebrush (*Artemisia filifolia* Nutt.) and yucca (*Yucca elata* Engelm.). A second objective of the study was to develop a methodology to permit estimation of $(SG)_e$ for shrubs that had not been tested in the wind tunnel.

THEORY

The small grain reference standard $(SG)_e$ has been defined as 0.254 m (10 in.) long, dry, small grain (wheat) stalks lying flat on the soil surface in rows perpendicular to wind direction with 0.254 m (10 in.) row spacing and stalks oriented parallel to the wind direction. Experimental data relating $(SG)_e$ to plant biomass can generally be closely fitted by an empirical prediction equation of the form

$$(SG)_e = a\, R_w^b \qquad [1]$$

where R_w is the air dry mass of aboveground vegetation cover and a, b are the prediction equation parameters whose value depends on the kind of vegetation cover (Lyles and Allison, 1981).

We can also expresss R_w as

$$R_w = \left[\frac{\rho\, N\, A_s}{A_T}\right] f(d) \qquad [2]$$

where

N/A_T = number of plants per unit area

A_s = silhouette area (projected area facing the flow)

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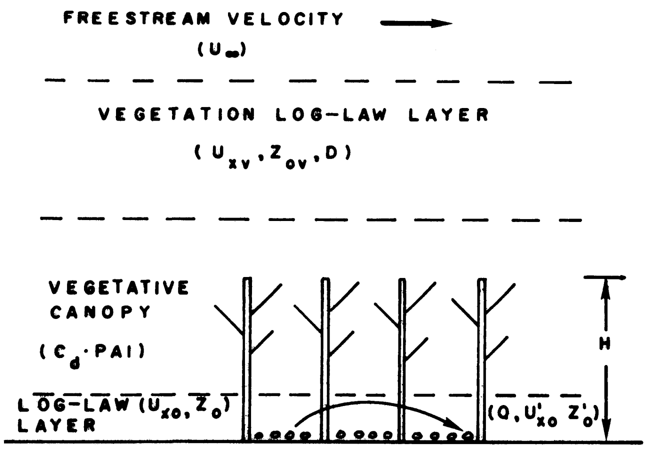

Fig. 1—Schematic representation of wind erosion and some of the important variables in a standing vegetative canopy.

p = plant density
f(d) = some function of plant thickness parallel to the flow

For example, with standing stalks, A_s = height times diameter and $f(d) = \pi\frac{d}{4}$, where d is stalk diameter. The term ($N\ A_s/A_T$) is often referred to as the plant area index (PAI). Using PAI equation [1] can be rewritten as

$$(SG)_e = C(PAI)^b \qquad [3]$$

where C is a new parameter.

The $(SG)_e$ can also be expressed as the rate of sand flux {q(kg/m·s)} below a vegetative canopy. An empirical fit of data from Lyles and Allison (1980) shows that for $(SG)_e > 200$ kg/ha

$$(SG)_e = C_1 - C_2 \ln(q) \qquad [4]$$

where C_1 and C_2 are constants. Fryrear (1985) has summarized wind erosion soil loss data from a variety of experiments and found a similar expression that fit the data.

Wind erosion in a standing vegetative canopy is illustrated in Fig. 1, where q below the canopy is a function of surface saltation friction velocity (U'_{*0}). Assuming that Bagnold's formulation (Greeley and Iverson, 1985) holds below a canopy, then

$$q \cong C_3\ U'^{3}_{*0} \qquad [5]$$

where C_3 is a constant. Other wind tunnel measurements (Lyles and Allison, 1976) have shown that the relationship of friction velocity above the canopy (U_{*v}) to that below without saltation (U_{*0}) can be expressed as

$$\frac{U_{*v}}{U_{*0}} = C_4 + C_5(PAI) \qquad [6]$$

Using a numerical model of a complex plant canopy, Shaw and Pereira (1982) obtained a similar result. They also found that C_5 varied as the soil surface roughness below the canopy varied. Hence, with saltation, we will denote the constants as C_4 and C'_5 in equation [6].

Finally, Shaw and Pereira (1982) noted that it is really the product of the drag coefficient (C_d) and the plant area that depletes the momentum flux through the canopy. Hence, PAI should be replaced by $C_d \cdot PAI$ in equations [3] and [6]. However, for the stalks, branches, and stiff yucca leaves discussed in this work, $C_d \cong 1.0$. In canopies with a significant number of leaves that streamline with the air flow under erosive wind speeds, it appears necessary to weight C_d to reflect the proportionate areas of leaves and stalks. Shaw and Pereira (1982) used $C_d = 0.2$ for a growing corn canopy.

When measuring $(SG)_e$ in a wind tunnel, the freestream velocity (U_∞) is held constant. U_{*v} will then vary only in response to canopy surface roughness (Z_{ov}), which can be expressed in the form

$$U_{*v} = C_6\ Z^p_{ov} \qquad [7]$$

where C_6 and p are constants over a moderate range of Z_o (Lyles and Allison, 1979). Combining equations [3] through [7] gives

$$(SG)_e = C(C_d{\cdot}PAI)^b = C_1 - C_2 \ln \left\{ C_3 \left[\frac{C_6\ Z^p_{ov}}{C_4 + C'_5(C_d{\cdot}PAI)} \right] \right\} \qquad [8]$$

Equation [8] illustrtes that the $(SG)_e$ should only be a function of $C_d \cdot PAI$ and Z_{ov}. Further, at any fixed $C_d \cdot PAI$, variation in the prediction parameters, C and b, of $(SG)_e$ should be caused by differences in Z_{ov} among canopies.

EXPERIMENTAL PROCEDURE

With the help of the USDA, Soil Conservation Service, two range sites located in Stevens County in southwestern Kansas were selected for experimental study. The sites were relatively level and had nearly pure stands of either sand sagebrush or yucca with sparse, interspersed grass 0.01 to 0.05 m tall. Average height of sagebrush was 0.68 m and of yucca was 0.79 m. On each site, a triangularly shaped plot (base 116 m and height 99 m) was staked with the base oriented normal to the prevailing southerly wind direction. Instrument towers were placed windward (south) of each plot and leeward in the apex of the triangle at the north end of each plot. Sensitive cup anemometers, thermocouples, and a direction indicator were mounted on the windward tower. When the direction vane on the windward tower indicated southerly winds and the temperature profile indicated near neutral stability, the aerodynamic properties of the plot were measured at the leeward towers.

Two towers were used at the lee position. Sensitive cup anemometers were located on a portable tower at heights of 0.245, 0.508, and 0.762 m, and a small thermal velocity probe was located 0.005 m above the surface. To measure the average airflow in the canopy, the portable tower was moved to 10 positions along a line normal to the wind direction in 1 m increments. Wind speeds at each position were averaged for 5 min. In addition, wind speeds above the leeward canopy were also measured by cup anemometers on a fixed tower at 1.0, 1.5, 2.5, and 4.0 m above the surface.

Each main plot was divided into 90 subplots (5.5 × 12.0 m) by wire stake markers. Geometry of the plants intersecting a diagonal line on each subplot was measured. These measurements included height (h), maximum diameter (d_1), and minimum diameter (d_2) of the plants. Estimates of plot PAI were calculated from the sampled plant geometry and plant population. Wind speed measurments on the sagebrush canopy were obtained with plant populations of 1.05 and 0.73 plants/m^2 and in the yucca canopy with populations of 0.36, 0.29, 0.20 and 0.12 plants/m^2. Plant populations were varied by hand removal of the appropriate number of plants from each subplot area.

During plot thinning, the geometry of 88 randomly selected plants (≅1 per subplot) of each species was measured, and the plants were taken to the laboratory for drying and weighing. Multiple regression analysis was then used to develop relationships to describe above-ground biomass as a function of plant geometry.

A second subgroup of plants of each species was also taken to the laboratory for two tests. In the first test, the small grain equivalents for each species was determined. To accomplish this, standing plants were anchored to the wind tunnel floor at the same height as in the field. Plants somewhat smaller than the average plants in the field were selected because the largest plants would not fit in the wind tunnel without adversely influencing the flow. The plants were arranged in a diamond-shaped pattern with equidistant spacing between them over the entire wind tunnel floor. The wind tunnel is 1.52 m wide, 1.93 m high, and 16.46 m long with a 10-blade, variable-pitch, axivane fan mounted upwind to create a push-type, recirculating airflow.

Below the canopy, at the leeward end of the working section, two standard test trays 1.48 m long, 0.165 m wide, and 0.04 m deep (inside dimensions) were filled with 0.297 to 0.420 mm diameter sand and exposed for 5 min at 13.36 m/s freestream wind speed. Three replications of soil loss were measured for each canopy. Four to five plant populations of each species were placed in the tunnel to establish a relationship between sand-loss rate and dry weight per unit floor area of vegetation. The weights of flat, small grain stubble oriented in the reference manner needed to produce the same sand-loss rates had been measured in a prior study (Lyles and Allison, 1980). Using the above information, regression relationships were developed to express the small grain equivalent mass as a function of the dry mass of standing plants.

Pitot-static tubes were used to measure wind speed profiles above the canopy as well as in the canopy in the tunnel in a manner similar to the field measurements. Both the tunnel and field wind speed profiles were analyzed using a two-step procedure. First, the zero-plane displacement height (D) was calculated using the procedures outlined by Molion and Moore (1983), in which the bulk flow through the canopy was used as an input. Next, multiple wind speed profiles above each canopy were analyzed to calculate aerodynamic roughness length (Z_{ov}) using a least-squares technique recommended by Ling (1976).

In a final laboratory test, the plant silhouette area was measured in 0.08 m height increments using a leaf area meter or a caliper, if stem pieces were too large to fit the meter. Regression analyses were then used to develop relationships between plant silhouette area and plant aboveground dry biomass. In addition, relationships between live leaf area and live dry leaf biomass were developed for the yucca plants.

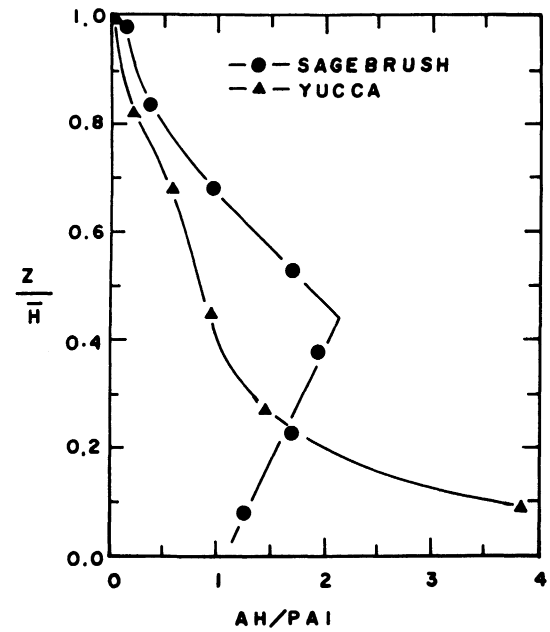

Fig. 2—Variation of non-dimensional plant area density with height. (Composite of 32 plants of each species.)

RESULTS AND DISCUSSION

The sagebrush and yucca canopies were quite different in form (Fig. 2). The height $(Zm/\bar{h}) = 0.44$ in the sagebrush, whereas A was maximum at the base of the leaves in the yucca canopy at about $Z/\bar{h} = 0.1$. Zm is height where A is maximum, and $\bar{h}$ is average canopy height above the surface.

The projected (silhouette) area per unit mass sagebrush increased rapidly with height (Fig. 3). In contrast, live yucca leaves maintained a nearly constant ratio of projected (silhouette) area to biomass over their height range.

Multiple linear regression analysis was used to relate dry, aboveground biomass [W_p(kg)] of 88 sagebrush plants to their geometry. The plants were selected at random from the test subplots and the relationship found was

$$\hat{W}_p = 0.6833\, h^{1.835} (d_1{}^2 + d_2{}^2)^{0.9545} , \quad R^2 = 0.92 \qquad [9]$$

where

h = plant height (m)
d_1 = maximum plant diameter (m)
d_2 = minimum plant diameter (m)

Sagebrush height in the subsample ranged from 0.33 to 1.04 m; maximum d_1 and d_2 were 1.80 and 1.12 m, respectively; and minimum d_1 and d_2 were 0.20 and 0.15 m, respectively.

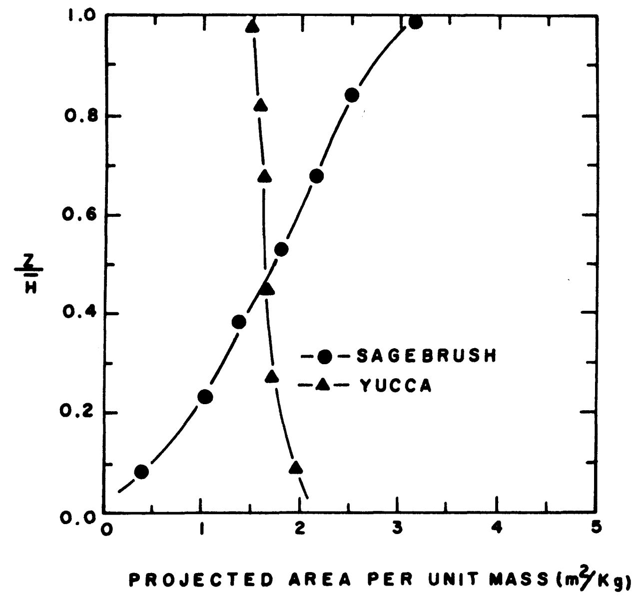

Fig. 3—Variation of projected area per unit mass with height. (Composite of 32 plants of each species.)

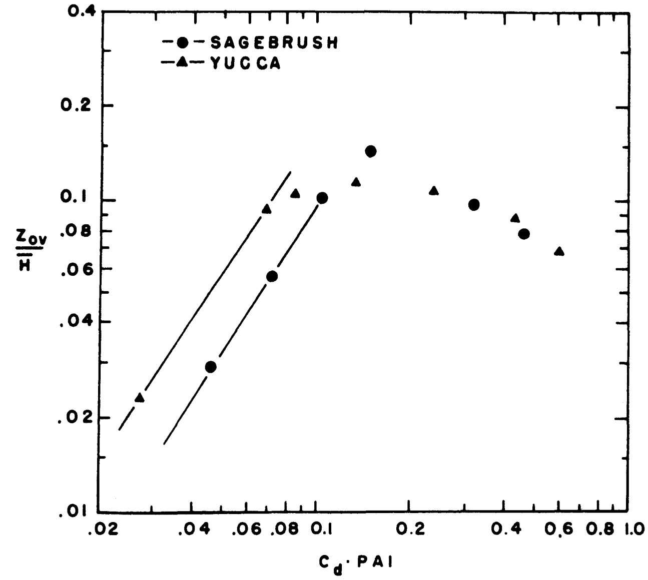

Fig. 4—Normalized roughness length as a function of C_d·PAI. Solid lines represent prediction equation [17]. Yucca: at C_d·PAI < 0.2, h = 0.44 m; C_d·PAI > 0.2, h = 0.79 m. Sagebrush: at C_d·PAI < 0.2, h = 0.526 m; C_d·PAI > 0.2, h = 0.68 m.

Linear regression analysis was also used to relate sagebrush plant silhouette area [$A_s(m^2)$] to W_p of 64 plants, which ranged from 0.2 to 12 kg. Because of the labor needed to determine area, only four plants > 4.0 kg were included in the sample. The relationship found was

$$\hat{A}_s = 0.01387\, W_p^{0.75} \;, \quad R^2 = 0.92 \qquad \ldots\ldots\ldots [10]$$

In a similar manner, 87 yucca plants were sampled at random from the test subplots and relationships between aboveground dry biomass (W_p(kg)) and plant geometry were developed as follows:

$$\hat{W}_p = 0.5944\, h^{1.76}\ (d_1{}^2 + d_2{}^2)^{1.053} \;,$$

$$R^2 = 0.80 \qquad \ldots\ldots\ldots [11]$$

The biomass in W_p consisted of that part of the fleshy root protruding above ground level, dead leaves generally flattened about the root, and live leaves.

Because the bulk of the standing PAI, and thus soil protection, is provided by the live leaves [W_L(kg)], a separate relationship was developed for them as follows:

$$\hat{W}_L = 0.2828\, h^{1.1706}\ [d_1{}^2 + d_2{}^2]^{1.1642} \;,$$

$$R^2 = 0.81 \qquad \ldots\ldots\ldots [12]$$

Finally, linear regression was used to develop a relationship between silhouette area of live leaves [$A_L(m^2)$] and W_L from a sample of 33 plants:

$$\hat{A}_L = 0.0023 + 1.786\, W_L \;, \; R^2 = 0.94 \qquad \ldots\ldots\ldots [13]$$

In yucca, the relationship between live leaf area and mass appears to remain linear as leaf size changes. The tallest yucca in this sample was 0.74 m.

From the wind tunnel tests, $(SG)_e$ was computed for the sagebrush and yucca on both a mass basis and a PAI basis. For sand sagebrush

$$(SG)_e = 0.1074\, R_w{}^{1.4181} = 48{,}126\ (PAI)^{1.4181} \;,$$

$$R^2\ 0.991 \qquad \ldots\ldots\ldots [14]$$

where $(SG)_e$ and R_w both have units of kg/ha.

For yucca, with R_w based on total above-ground biomass,

$$(SG)_e = 0.0939\, R_w{}^{1.3772} \;, \; R^2 = 0.995 \qquad \ldots [15]$$

For yucca, based on dry biomass of live leaves alone,

$$(SG)_e = 0.1408\, R_w{}^{1.3774} = 19{,}983\ (PAI)^{1.3774} \;,$$

$$R^2 = 0.995 \qquad \ldots\ldots\ldots [16]$$

The computed aerodynamic roughness lengths (Z_{ov}) for the tunnel and field tests are shown in Fig. 4. As Shaw and Pereira (1982) have shown, plant canopies of moderate height tend to have maximum roughness as C_d · PAI ranges from about 0.1 to 0.3. However, to compute $(SG)_e$ of low shrub canopies, we are particulrly interested in the behavior of Z_{ov} at values of C_d · PAI < 0.1 where wind erosion is likely to occur. It is generally recognized that in canopies, Z_{ov} scales with $\bar{h}$, and that with fixed plant geometry, $Z_{ov}/\bar{h}$ changes with PAI as plant population increases. In a relatively rigid canopy, two other variables appear important. For C_d · PAI < 0.1, $Z_{ov}/\bar{h}$ increases both as $Zm/\bar{h}$ increases (Shaw and Pereira, 1982) and as a characteristic width [w(m)] or diameter of the roughness elements increase (Lyles and Allison, 1979). Evidently, wide roughness elements increase the scale of turbulence and, thus, the apparent roughess of the canopy.

An empirical relation was fitted to the sagebrush and yucca canopy data to predict Z_{ov} for C_d · PAI < 0.01, in

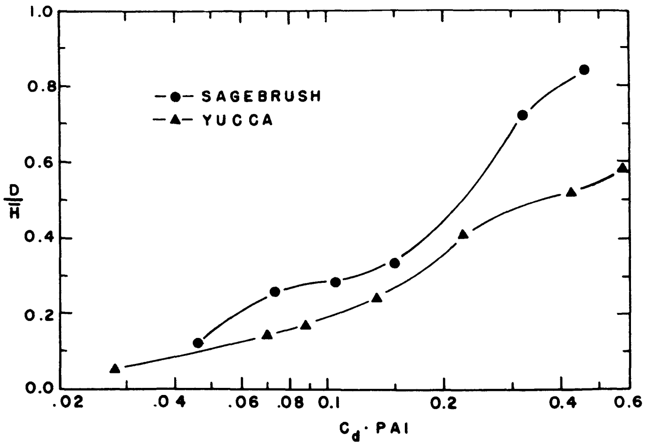

Fig 5—Normalized zero plane deplacement height as a function of C_d·PAI. Yucca: at C_d·PAI < 0.2, h = 0.44 m; C_d·PAI > 0.2, h = 0.79 m. Sagebrush: at C_d·PAI < 0.2, h = 0.53 m; C_d·PAI > 0.2, h = 0.68 m.

which PAI, Zm/$\bar{h}$, and w were considered to be the important parameters. As a result,

$$\ln\left(\frac{Z_{ov}}{\bar{h}}\right) = 1.5 + 1.55 \ln (C_d \cdot PAI) + 0.15 \left[2.3 + \ln\left(\frac{Zm}{\bar{h}}\right)\right] + 0.4 \ln(100w) \quad \ldots\ldots [17]$$

where w was 0.0025 and 0.02 m for the sagebrush and yucca, respectively. The parameters in equation [17] should be limited to the following ranges: $0.002 \leqslant w \leqslant 0.04$, $0.1 \leqslant (Zm/\bar{h}) \leqslant 1.0$, $C_d \cdot PAI < 0.1$ and $\bar{h} < 1.5$ m.

The aerodynamic displacement height (D) was computed from measurements of bulk flow through the canopies (Fig. 5). This method of computation resulted in D values lower than those calculated by Shaw and Pereira (1982) for a corn canopy. However, more airflow would be expected to penetrate the rigid shrub canopies studied here, thus, producing lower values of D. At very low plant populations ($C_d \cdot$ PAI), D tends to decrease toward that of the underlying surface.

To further explore the theory presented in this work, we will employ an additional data set previously reported by Lyles and Allison (1981). In the earlier study, stubble from six different standing crops was tested for $(SG)_e$. The crop characteristics along with those of the sagebrush and yucca used in this study are given in Table 1. The crop stubble mainly resembled tapered cylinders, except for the cotton, which had occasional upper branches, and the rape, which had several branches near the top of the canopy.

Values of the parameter C were calculated for all eight canopies so their $(SG)_e$ could be compared at equal values of $C_d \cdot$ PAI (Fig. 6). $(SG)_e$ for the winter wheat was recomputed from the original soil loss data and was somewhat higher than the value previously reported. Nevertheless, the slope of the wheat curve appears to be too steep in comparison with the other cylindrical crops.

There is a tendency for the slope of the curves in Fig. 6 to increase as $(SG)_e$ decreases at a given $C_d \cdot$ PAI. Using this fact, numerical iteration was performed to recompute the parameters b and C for the curves in Fig. 6 and find a relationship between b and C. The result was

$$\hat{b} = 3.42 - 0.211 \ln (C^{\prime}) \ , \ 1.12 \leqslant \hat{b} \leqslant 1.35 \quad \ldots [18]$$

The fit to the curves in Fig. 6 was then tested using $\hat{b}$ and recomputed C ($C^{\prime}$); $(SG)_e$ could be closely estimated ($R^2 = 0.999$) in the C_d·PAI range 0.01 to 0.1. Finally values of ln (Z_{ov}) were computed at $C_d \cdot PAI = 0.05$ for all plants in Table 1, except wheat, and plotted against ln $C^{\prime}$ (Fig. 7). Linear regression was then used to develop an estimating equation for $C^{\prime}$ as

$$\hat{C} = \frac{499.943}{Z_{ov}^{0.9741}} \ , \ R^2 = 0.97 \quad \ldots\ldots [19]$$

TABLE 1. GEOMETRY OF STANDING PLANTS TESTED IN WIND TUNNEL (SIX CROP PLANTS ARE DATA FROM LYLES AND ALLISON (1981)

	Char. width, m	Density, Mg/m^3	Average height, m	Row § spacing, m	$\frac{Zm}{h}$ ‖
Forage sorghum (*Sorghum bicolor* (L.) Moench.)	0.0138*	0.38	0.159	0.762	0.1
Silage corn (*Zea mays* L.)	0.0251*	0.20	0.159	0.762	0.1
Cotton (*Gossypium hirsutum* L.)	0.0078*	0.56	0.343	0.762	0.1
Rape (*Brassica rapa* L.)	0.0059*	0.26	0.254	0.254	1.0
Winter wheat (*Triticum aestivum* L.)	0.0029*	0.16	0.254	0.254	0.1
Sunflowers (*Helianthus annuus* L.)	0.0157*	0.26	0.432	0.762	0.1
Sand sagebrush (*Artemisia filifolia* Nutt.)	0.0025†		0.526	0.73-1.39	0.44
Yucca (*Yucca elata* Engelm.)	0.020‡		0.440	0.73-2.18	0.1

* Average diameter of stalk
† Average diameter of fine stem
‡ Average leaf width
§Wind direction normal to rows
‖ Ratio of height of maximum area density to average plant height

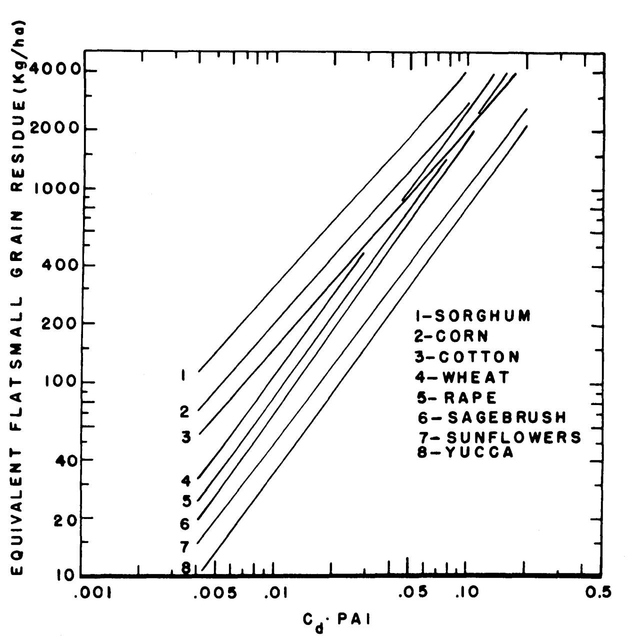

Fig. 6—Equivalent flat small-grain residue as a function of the product of drag coefficient (C_d) and plant area index (PAI) for crop stalks and shrubs.

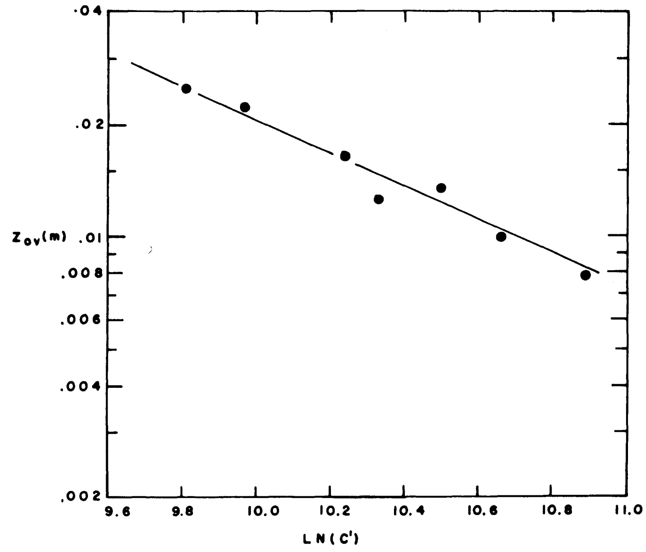

Fig. 7—Predicted roughness length (Z_{ov}) at C_d·PAI equal 0.05 as a function of the parameter C'.

using Z_{ov} at $C_d \cdot$ PAI = 0.05. The relationship in Fig. 7 substantiates the theoretical hypothesis suggested earlier in equation [8] that at a fixed $C_d \cdot$ PAI, the prediction parameters (C and b) should be a function of Z_{ov}.

An important use of the preceding prediction equations is to estimate the $(SG)_e$ of untested shrub or stubble canopies, which are relatively rigid. We will illustrate the procedure using the winter wheat stubble whose characteristics are listed in Table 1. Beginning with equation [17], $Z_{ov} = 0.0067$ m at $C_d \cdot$ PAI = 0.05. Next, using Z_{ov} in equation [19] gives C = 65,545.2, and using C in equation [18] gives b = 1.08. Finally, using equation [3], we can estimate $(SG)_e$ = 5452, 2579, and 454 kg/ha at $C_d \cdot$ PAI = 0.1, 0.05, and 0.01, respectively. The predicted C was within 5% of the measured C. However, the predicted slope, b, forces the wheat to resemble the slope of the other stubble crops and, thus, predicts $(SG)_e$ values somewhat larger than the sorghum stubble $(SG)_e$ at equal $C_d \cdot$ PAI values. The predicted $(SG)_e$ for the wheat appears to fit the overall data pattern better than the measured values. Additional measurements are needed to validate the predicted value, however.

To this point the discussion has been aimed at finding $(SG)_e$ of single species, but rangelands are usually composed of mixtures of grasses and shrubs. Until further testing can be done, Lyles and Allison (1980) have shown the geometric mean can be used to approximate the $(SG)_e$ of mixtures. It can be computed as follows:

$$(SG)_e = (SG)_{eTi}^{Pi} \cdot (SG)_{eTi+1}^{Pi+1} \cdot (SG)_{eTi+2}^{Pi+2} \cdots \quad [20]$$

where Pi is the proportion of aboveground biomass of each species in the mixture; $(SG)_{eTi}$ is the small grain equivalent computed by using the total aboveground biomass of the mixture and treating it as if it were all composed of the ith species.

CONCLUSIONS

The $(SG)_e$ of a plant canopy depends on the magnitude of the friction velocity reaching an underlying erodible surface. At constant wind tunnel freestream or geostrophic outdoor wind speeds, friction velocity above the canopy depends on the aerodynamic roughness length (Z_{ov}) of the canopy and underlying surface, whereas depletion of the friction velocity through the canopy appears to be a linear function of canopy $C_d \cdot$ PAI. Thus, knowledge of canopy Z_{ov} at a fixed $C_d \cdot$ PAI can be used to estimate the prediction parameters (C and b) which, along with actual canopy $C_d \cdot$ PAI, allow one to predict $(SG)_e$ for a shrub or stubble canopy.

Direct wind tunnel measurement remains the most accurate method of evaluating plant canopy $(SG)_e$. However, the methodology and prediction equations presented here can be used to provide adequate estimates of $(SG)_e$ in rigid shrub or stubble canopies when wind tunnel estimates are not available. In sand sagebrush and yucca rangeland canopies, simple regression prediction equations developed in this study can provide useful estimates of plant silhouette area from measurements of either plant weight or plant geometry. For sand sagebrush or yucca canopies near 0.5 m tall, mass or PAI of the canopies can be used directly to predict $(SG)_e$ using the estimating equations developed in this study.

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